

# Anomalous $g_5^Z$ Coupling at $\gamma\gamma$ Colliders

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## Abstract

We study the constraints on the anomalous coupling  $g_5^Z$  that can be obtained from the analysis of the reaction  $\gamma\gamma \rightarrow W^+W^-Z$  at future linear  $e^+e^-$  colliders. We find out that a 0.5 (1) TeV  $e^+e^-$  collider operating in the  $\gamma\gamma$  mode can probe values of  $g_5^Z$  of the order of 0.15 ( $4.5 \times 10^{-2}$ ) for an integrated luminosity of  $10 \text{ fb}^{-1}$ . This shows that the ability to search for this anomalous interaction of the  $\gamma\gamma$  mode is better than the one of the usual  $e^+e^-$  mode, and it is similar to the ability of the  $e\gamma$  mode.

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## I. INTRODUCTION

The mechanism for breaking the symmetry of the electroweak interactions has not been directly accessed in experiments thus far. One possibility is that the Higgs boson is so heavy that it will not be produced even in the next generation of colliders. In this case and in other strongly interacting symmetry-breaking scenarios, it is interesting to parametrize the symmetry-breaking sector in a model independent way through the use of chiral lagrangians [1]. In this approach, the low energy effects of new physics are represented by an infinite tower of non-renormalizable effective operators which are consistent with the  $SU(2)_L \otimes U(1)_Y$  symmetry of the standard model (SM).

The lowest order chiral Lagrangian exhibits an universal behavior for the dynamics of the electroweak interactions, being independent of the details of the mechanism of symmetry-breaking. However, at the next-to-leading order in the chiral expansion, there are 14 effective operators whose coefficients are dictated by the underlying dynamics. Among the next-to-leading operators, there is only one that is CP conserving but parity violating [2]. This operator also breaks the custodial  $SU(2)_C$  symmetry [3] and is given by

$$\mathcal{L}_{11} = \alpha_{11} g \epsilon^{\alpha\beta\mu\nu} \text{Tr} \left( \tau^3 U^\dagger D_\mu U \right) \text{Tr} \left( U^\dagger W_{\alpha\beta} D_\nu U \right) , \quad (1)$$

where the dimensionless unitary unimodular matrix  $U = \exp(i\xi^a \tau^a / v^2)$  contains the would-be Goldstone bosons  $\xi^a$ ,  $v \simeq 246$  GeV is the symmetry-breaking scale, the  $SU(2)_L \otimes U(1)_Y$  covariant derivative is

$$D_\mu U = \partial_\mu U + i \frac{g}{2} W_\mu^j \tau^j U - i \frac{g'}{2} B_\mu U \tau^3 , \quad (2)$$

and the field strength tensors are written in terms of  $W_\mu = W_\mu^j \tau^j$

$$W_{\mu\nu} = \frac{1}{2} \left( \partial_\mu W_\nu - \partial_\nu W_\mu + \frac{i}{2} [W_\mu, W_\nu] \right) , \quad (3)$$

$$B_{\mu\nu} = \frac{1}{2} (\partial_\mu B_\nu - \partial_\nu B_\mu) \tau^3 . \quad (4)$$

The physical content of the above operator is more transparent in the unitary gauge,  $U = 1$ , where the effective Lagrangian (1) gives rise to anomalous contributions to the triple

vertex  $W^+W^-Z$  and to the four-gauge-boson vertex  $W^+W^-Z\gamma$ . In the standard notation of Ref. [4], we have the correspondence for the triple gauge-boson vertex

$$g_5^Z = \frac{e^2}{s_W^2 c_W^2} \alpha_{11} , \quad (5)$$

where we denote the sine (cosine) of the weak mixing angle by  $s_W$  ( $c_W$ ). The expected size of  $g_5^Z$  depends upon whether or not the underlying dynamics respects the custodial symmetry. In models with a custodial symmetry,  $g_5^Z$  should be of the order of  $10^{-4}$ , while for models without this symmetry we expect  $g_5^Z \sim 10^{-2}$ .

At low energies, the bounds on this operator come from one-loop contributions to meson decays and to the vertex  $Zff$ . From the study of the decay  $K_L \rightarrow \mu^+\mu^-$ , we obtain limits of the order  $g_5^Z \lesssim 1$  [5], while the precise measurements of the  $Z$  flavor diagonal couplings imply that  $g_5^Z \lesssim 0.04$  [6]. These bounds are obtained using the naturalness assumption that no cancellations take place between contributions from different anomalous interactions. However, a closer look at the interaction (1) reveals that it is momentum dependent, and consequently it can be better studied directly in processes at high energies.

The Next Linear  $e^+e^-$  Collider (NLC) [7] will reach a center-of-mass energy between 500 and 2000 GeV with an yearly integrated luminosity of at least  $10 \text{ fb}^{-1}$ . An interesting feature of this new machine is the possibility of transforming an electron beam into a photon one through the laser backscattering mechanism [8,9]. This process will allow the NLC to operate in three different modes,  $e^+e^-$ ,  $e\gamma$ , and  $\gamma\gamma$ , opening up the opportunity for a wider search for new physics. However, it is important to stress that the collider can operate in only one of its three modes at a given time, therefore, it is imperative to study comparatively the different features of each of these setups.

Previously, the phenomenological implications of the operator (1) to the reaction  $e^+e^- \rightarrow W^+W^-Z$  at high energies were analyzed in Ref. [10], which showed that it is possible to obtain limits of the order of  $g_5^Z \lesssim 0.3$  for a center-of-mass energy of 500 GeV. However, this sensitivity to  $g_5^Z$  can only be achieved for a high degree of  $e^-$  polarization. This interaction was also studied in  $e\gamma$  collisions in Ref. [11] through the process  $e^-\gamma \rightarrow W^-Z\nu_e$ , that

will be able to lead to constraints  $g_5^Z \lesssim 0.12$  for a center-of-mass energy of 500 GeV and an integrated luminosity of  $10 \text{ fb}^{-1}$ . It is interesting to notice that the bounds obtained in the above processes originate from the direct tree-level contributions of the anomalous interaction.

In this work we examine the capability of the next generation of  $e^+e^-$  colliders operating in the  $\gamma\gamma$  mode to place direct bounds on the effective operator (1) through the reaction  $\gamma\gamma \rightarrow W^+W^-Z$  [12,13]. In a  $\gamma\gamma$  collider, this process exhibits tree-level contributions from the anomalous interaction (1) and contains the minimum number of final state particles. We show that for a center-of-mass of 500 (1000) GeV it is possible to obtain bounds  $g_5^Z \lesssim 0.15$  ( $4.5 \times 10^{-2}$ ) for an integrated luminosity of  $10 \text{ fb}^{-1}$ .

## II. RESULTS

The most promising mechanism to generate hard photon beams in an  $e^+e^-$  linear collider is laser backscattering. Assuming unpolarized electron and laser beams, the backscattered photon distribution function [9] is

$$F_{\gamma/e}(x, \xi) \equiv \frac{1}{\sigma_c} \frac{d\sigma_c}{dx} = \frac{1}{D(\xi)} \left[ 1 - x + \frac{1}{1-x} - \frac{4x}{\xi(1-x)} + \frac{4x^2}{\xi^2(1-x)^2} \right], \quad (6)$$

with

$$D(\xi) = \left( 1 - \frac{4}{\xi} - \frac{8}{\xi^2} \right) \ln(1 + \xi) + \frac{1}{2} + \frac{8}{\xi} - \frac{1}{2(1 + \xi)^2}, \quad (7)$$

where  $\sigma_c$  is the Compton cross section,  $\xi \simeq 4E\omega_0/m_e^2$ ,  $m_e$  and  $E$  are the electron mass and energy respectively, and  $\omega_0$  is the laser-photon energy. The quantity  $x$  stands for the ratio between the scattered photon and initial electron energy and its maximum value is

$$x_{\max} = \frac{\xi}{1 + \xi}. \quad (8)$$

In what follows, we assume that the laser frequency is such that  $\xi = 2(1 + \sqrt{2})$ , which leads to the hardest possible spectrum of photons with a large luminosity.

The cross section for  $W^+W^-Z$  production via  $\gamma\gamma$  fusion can be obtained by folding the elementary cross section for the subprocesses  $\gamma\gamma \rightarrow W^+W^-Z$  with the photon-photon luminosity ( $dL_{\gamma\gamma}/dz$ ), *i.e.*,

$$d\sigma(e^+e^- \rightarrow \gamma\gamma \rightarrow WWZ)(s) = \int_{z_{\min}}^{z_{\max}} dz \frac{dL_{\gamma\gamma}}{dz} d\hat{\sigma}(\gamma\gamma \rightarrow WWZ)(\hat{s} = z^2 s) , \quad (9)$$

where  $\sqrt{s}$  ( $\sqrt{\hat{s}}$ ) is the  $e^+e^-$  ( $\gamma\gamma$ ) center-of-mass energy,  $z^2 = \tau \equiv \hat{s}/s$ , and the photon-photon luminosity is

$$\frac{dL_{\gamma\gamma}}{dz} = 2 z \int_{z^2/x_{\max}}^{x_{\max}} \frac{dx}{x} F_{\gamma/e}(x, \xi) F_{\gamma/e}(z^2/x, \xi) . \quad (10)$$

The analytical calculation of the cross section for the subprocess  $\gamma\gamma \rightarrow W^+W^-Z$  requires the evaluation of 12 Feynman diagrams in the unitary gauge and it is very lengthy and tedious despite being straightforward. We evaluated numerically the helicity amplitudes for this process using the techniques outlined in Refs. [14,15] in order to obtain our results in an efficient and reliable way. As a check of our results, we explicitly verified that the amplitudes were Lorentz and  $U(1)_{em}$  invariant. The phase space integrations were performed numerically using the Monte Carlo routine VEGAS [16].

The total cross section for the process  $\gamma\gamma \rightarrow W^+W^-Z$  is a quadratic function of the anomalous coupling  $g_5^Z$ , *i.e.*

$$\sigma_{\text{tot}} = \sigma_{\text{sm}} + g_5^Z \sigma_{\text{int}} + (g_5^Z)^2 \sigma_{\text{ano}} , \quad (11)$$

where  $\sigma_{\text{sm}}$  stands for the SM cross section [12] and  $\sigma_{\text{int}}$  ( $\sigma_{\text{ano}}$ ) is the interference (pure anomalous) contribution. We evaluated these contributions for unpolarized backscattered photons imposing that the polar angles of the produced vector bosons with the beam pipe are larger than  $10^\circ$ . In Table I, we present our results for several  $e^+e^-$  center-of-mass energies. The interference term vanishes since the anomalous amplitude has a phase of  $90^\circ$  with respect to the standard model amplitude for an unpolarized initial state.

In order to quantify the effect of the new couplings, we defined the statistical significance  $\mathcal{S}$  of the anomalous signal

$$\mathcal{S} = \frac{|\sigma_{\text{tot}} - \sigma_{\text{sm}}|}{\sqrt{\sigma_{\text{sm}}}} \sqrt{\mathcal{L}} , \quad (12)$$

which can be easily evaluated using the parametrization (11) with the coefficients given in Table I. We list in Table II the values of the anomalous couplings that correspond to a  $3\sigma$  effect in the total cross section for the different center-of-mass energies of the associated  $e^+e^-$  collider, assuming an integrated luminosity  $\mathcal{L} = 10 \text{ fb}^{-1}$ . From this table, we can learn that a  $\gamma\gamma$  collider leads to bounds on  $g_5^Z$  that are better than the ones that can be obtained in the usual  $e^+e^-$  mode. Moreover,  $\gamma\gamma$  and  $e\gamma$  collider lead to similar constraints on  $g_5^Z$ .

The kinematical distributions of the final state particles can be used, at least in principle, to increase the sensitivity of the  $\gamma\gamma$  reactions to anomalous interactions, improving consequently the bounds on them. In order to reach a better understanding of the effects of the anomalous interaction (1) in the reaction  $\gamma\gamma \rightarrow W^+W^-Z$ , we present in Fig. 1–3 various representative distributions of the final state gauge bosons, adopting the values of the anomalous coupling constants that lead to a  $3\sigma$  deviation in the total cross section.

In Fig. 1 we show the normalized distribution in the rapidity  $y_W$  of the  $W^\pm$  for a center-of-mass energy of 0.5 and 1 TeV. The distributions for  $W^+$  and  $W^-$  coincide due to the absence of the interference term in the cross section. It is interesting to notice that the anomalous coupling  $g_5^Z$  enhances the production of  $W^\pm$  in the central region of the detector, where they can be more easily reconstructed. Furthermore, increasing the center of mass energy, the  $W$ 's tend to populate the high rapidity region, as it happens in the process  $\gamma\gamma \rightarrow W^+W^-$ . Consequently, the cut in the  $W$  angle with beam pipe discards a larger fraction of events at high energies.

The normalized invariant mass distributions of  $W^\pm Z$  pairs are presented in Fig. 2 for a center-of-mass energy of 0.5 and 1 TeV. Once again the  $W^+Z$  and  $W^-Z$  curves coincide. From this Figure we can learn that the presence of the anomalous interaction increases slightly the invariant mass of the  $W^\pm Z$  pairs since the new couplings are proportional to the photon momentum. Moreover, as the center-of-mass energy of the collider is increased, the distributions broaden and shift toward higher invariant masses.

Figure 3 shows the laboratory energy distribution of the  $Z$  gauge boson. As we can see from this figure, the introduction of the anomalous interaction favors the production of more energetic  $Z$  bosons, because of the new momentum-dependent couplings. At lower center-of-mass energies the distribution is rather peaked around small values for the energy of the  $Z$  boson because of the available phase space. However, as the center-of-mass energy of the collider increases, the distributions broaden, exhibiting many  $Z$  bosons with high energies.

Up to this point we were able to demonstrate that a  $\gamma\gamma$  collider can reveal the existence of an anomalous interaction such as the one described by (1). However, the determination that the anomalous events are because of this interaction is a much harder task. In principle this could be done through the study of kinematical distributions. Notwithstanding, several anomalous interactions lead to distributions similar to the ones that we presented, see for instance Ref. [13]. The effective operator (1) could be singled out through the forward-backward asymmetry associated to parity violation, however, this does not happen for unpolarized photons since the interference term vanishes, see Table I. Therefore, in order to determine which anomalous interaction is responsible for the anomalous events we must employ polarized backscattered photons. As an illustration, we show in Fig. 4 the normalized  $W^\pm$  rapidity distributions for the subprocess  $\gamma\gamma \rightarrow W^+W^-Z$  with  $\sqrt{s} = 0.5$  TeV, assuming that one photon has a left-handed polarization while the other is right-handed. As we can see from this figure, the rapidity distribution for the  $W^+$  and  $W^-$  do not coincide, despite the result being clearly  $CP$  invariant. This a feature unique to the anomalous interaction (1).

### III. CONCLUSIONS

We analyzed in this work the capability of an  $e^+e^-$  collider operating in the  $\gamma\gamma$  mode to unravel the existence of the anomalous interaction (1). We demonstrated that for a center-of-mass energy of 0.5 (1) TeV and an integrated luminosity of  $10 \text{ fb}^{-1}$ , the study of the reaction  $\gamma\gamma \rightarrow W^+W^-Z$  can lead to bounds  $|g_5^Z| \leq 0.15 (4.5 \times 10^{-2})$ . These bounds are

similar to the ones that can be obtained in the  $e\gamma$  mode of the collider and are better than the one stemming from the usual  $e^+e^-$  mode. Moreover, at higher energies the luminosity of  $\gamma\gamma$  colliders can be larger than the corresponding  $e\gamma$  because of problems in the construction this last mode [17]. Consequently, the  $\gamma\gamma$  mode will be the most powerful one to analyze the  $g_5^Z$  anomalous coupling.

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## TABLES

$\sqrt{s}$	0.5 TeV	1 TeV	2.0 TeV
$\sigma_{\text{sm}}$	18.7	238.	548.
$\sigma_{\text{int}}$	0	0	0
$\sigma_{\text{ano}}$	179.	$7.27 \times 10^3$	$142. \times 10^3$

 TABLE I. Cross sections  $\sigma_{\text{sm}}$ ,  $\sigma_{\text{int}}$ , and  $\sigma_{\text{ano}}$  in fb.

$\sqrt{s}$	0.5 TeV	1 TeV	2 TeV
$g_5^Z$	(-0.15, 015)	$(-4.5 \times 10^{-2}, 4.5 \times 10^{-2})$	$(-1.2 \times 10^{-2}, 1.2 \times 10^{-2})$
$\Delta\sigma$	4.14	14.6	22.2

TABLE II. Allowed intervals of  $g_5^Z$  for an effect smaller than  $3\sigma$  in the total cross section. We also exhibit the difference ( $\Delta\sigma$ ) between the anomalous cross sections and the SM ones in fb for a  $3\sigma$  effect.

## FIGURES

FIG. 1. Normalized rapidity distribution of the produced  $W^\pm$ . The solid (dashed) stands for the SM prediction and the dotted (dot-dashed) one represents the results for  $g_5^Z = 0.15$  ( $4.5 \times 10^{-2}$ ) at a center-of-mass energy of 0.5 (1) TeV.

FIG. 2. Normalized invariant mass distribution of pairs  $W^\pm Z$ . The conventions are the same as in Fig. 1.

FIG. 3. Normalized energy distribution of the  $Z$  boson. The conventions are the same as in Fig. 1.

FIG. 4. Normalized rapidity distribution of the  $W^\pm$  bosons for the subprocess  $\gamma\gamma \rightarrow W^+W^-Z$  at  $\sqrt{\hat{s}} = 0.5$  TeV, using  $g_5^Z = 0.15$  and that one photon is left-handed while the other is right-handed. The solid line stands for the SM result, while the dotted (dashed) line represents the anomalous result for the  $W^+$  ( $W^-$ ) rapidity.

Fig. 1

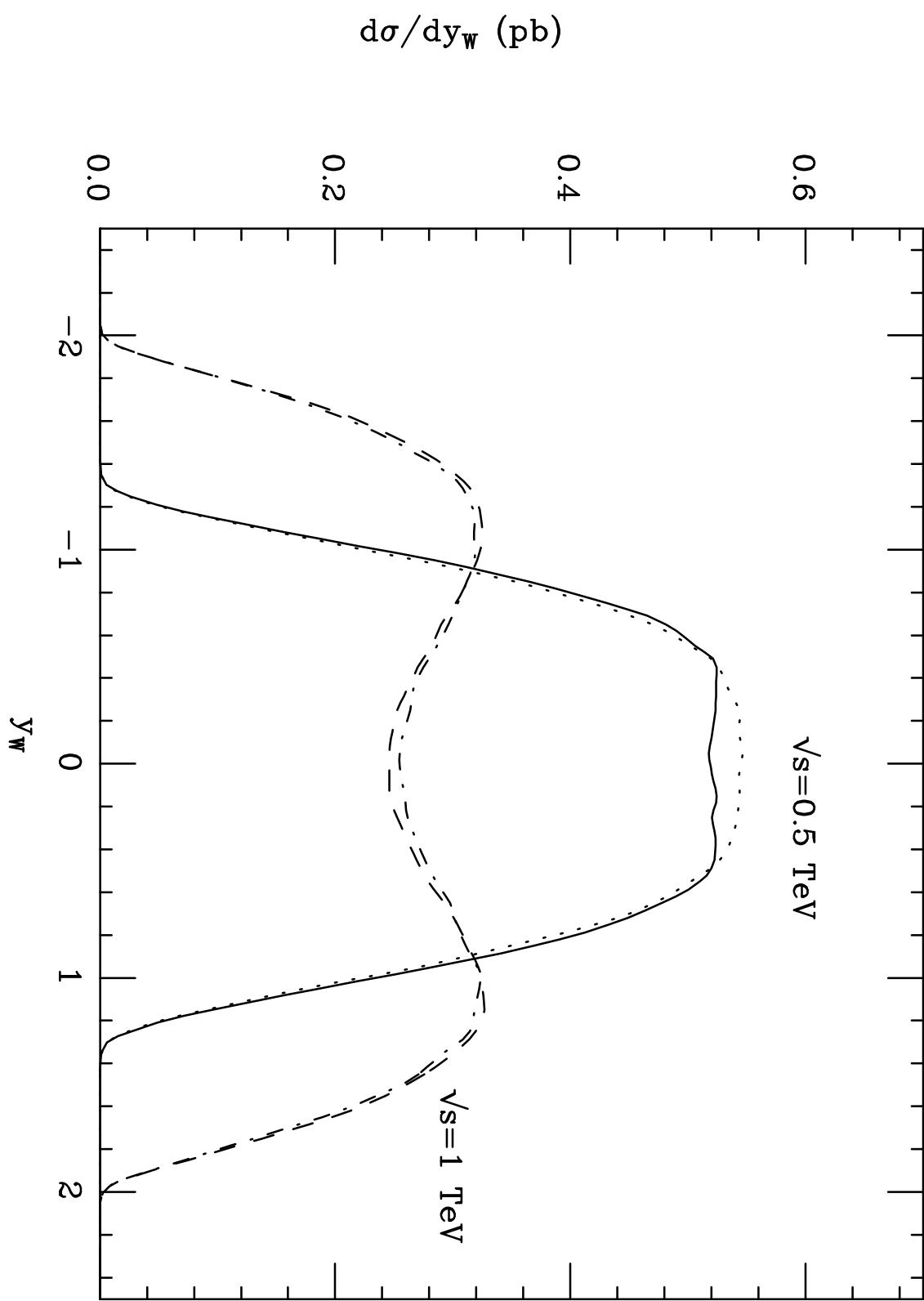


Fig. 2

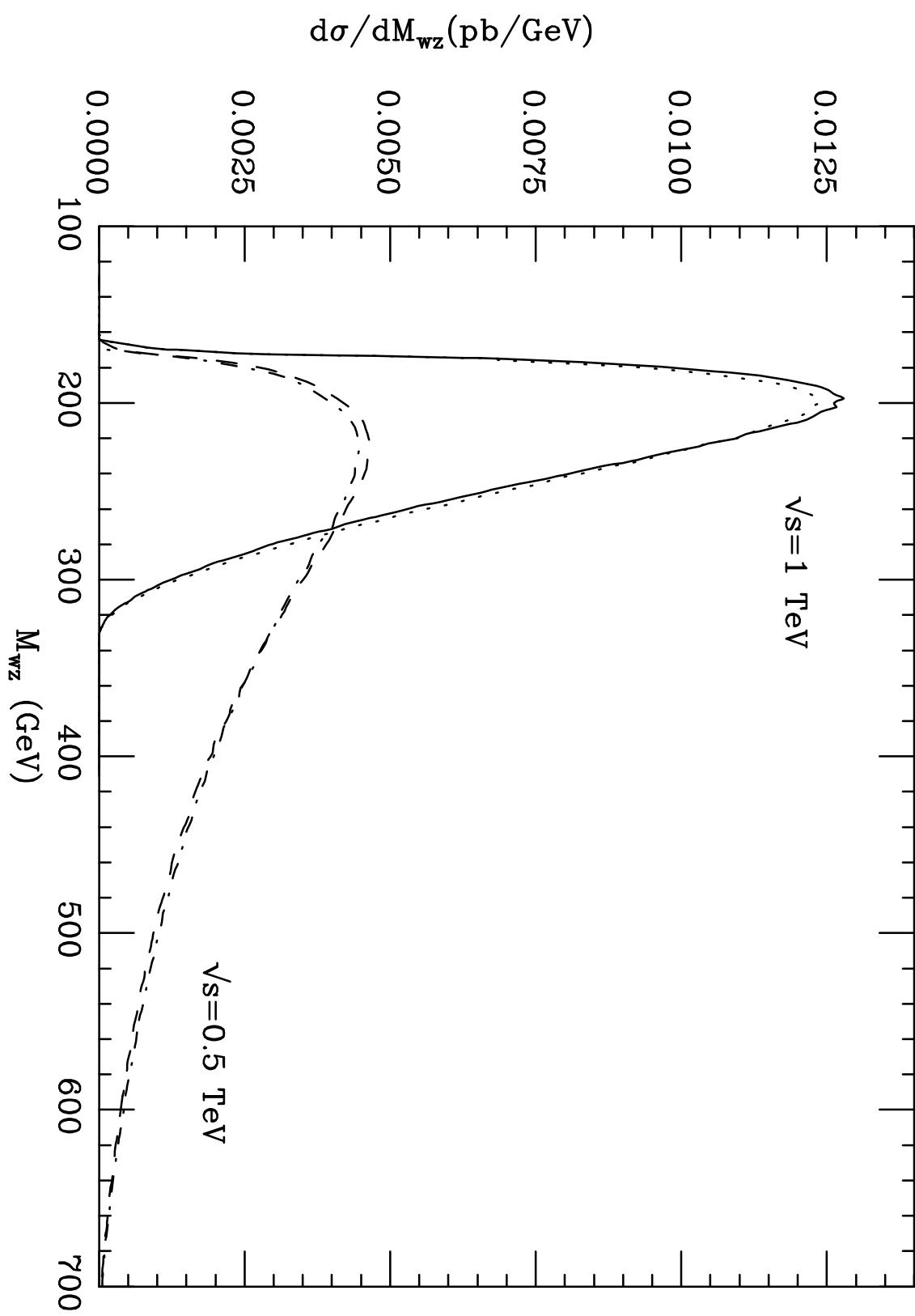


Fig. 3

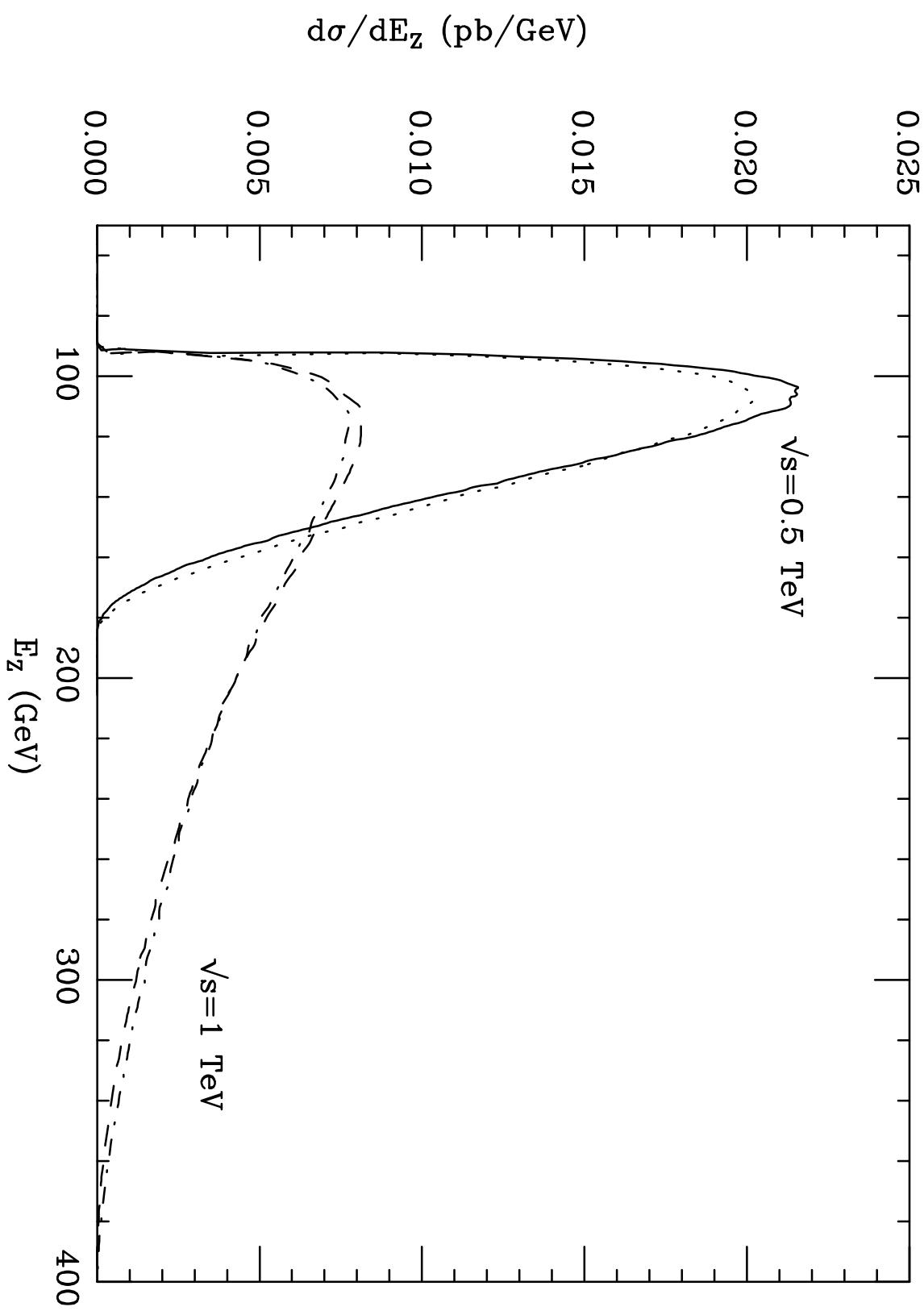


Fig. 4

